# Failure analysis method for enhancing circularity through systems perspective



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# Failure analysis method for enhancing circularity through systems perspective

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## Abstract

Recently, a circular economy has attracted global attention as an approach for addressing material security and resource-efficiency issues. As our societies shift toward a circular economy, manufacturers need to not only produce environmentally conscious products but to also realize reliable systems that will ensure the closure of the loops of the products, components, and materials. To do so, early-stage design is crucial to effectively and efficiently detect possible failures and then take adequate countermeasures against them. Although a few methods of failure analysis have been proposed to address environmental issues, these methods have failed to consider the cause–effect relationships among failures. This will hinder manufacturers from identifying core problems that should be addressed in a given system. Therefore, this study extends failure mode and effect analysis, which is an engineering technique used to address potential failures, by addressing the entire system reliability in relation to circularity. As a result of a case study of a manufacturer aiming to increase circularity with their products on the market, we revealed that the proposed method is useful in the early stage of design to (a) identify failure modes where effects are largely given to or received from other failures, (b) develop countermeasures effectively by addressing root causes of failures, and (c) find an opportunity to collaborate with external actors.

KEYWORDS
circular economy, decision-making trial and evaluation laboratory (DEMATEL), failure mode and effect analysis (FMEA), industrial ecology, product-service system (PSS), system design

## 1 | INTRODUCTION

In recent decades, manufacturing industries have faced the challenge of lowering the environmental impacts of product lifecycles (Alting & Legarth, 1995; Herrmann, Hauschild, Gutowski, & Lifset, 2014). In addition, these industries are challenged by our societies' increased interest in a circular economy (CE), "which is restorative by design, and which aims to keep products, components and materials at their highest utility and value, at all times" (Webster, 2015), partly due to the issue of material security (Commission, 2014, 2015). For a manufacturing company, these challenges are often addressed to create value together with the requirement of the fundamental quality, such as the malfunction probability of a product (Finster, Eagan, & Hussey, 2001; Umeda et al., 2012). As yet another challenge, manufacturers' scope of design objects has, in many cases, expanded to larger systems (even a system of systems) (Haskins, Forsberg, & Krueger, 2006; Lindemann, 2011), such that services are included (Tukker, 2015) and stakeholders beyond customers and product users must be addressed properly (Donaldson, Ishii, & Sheppard, 2004). Addressing all these challenges while remaining competitive on the markets (Da Silveira, 2014) is highly demanding.

Design, especially an early stage of design, is critical for a manufacturer to effectively address these challenges due to its high impact on the product lifecycle performance (Fabrycky, 1987; Hollins & Pugh, 1990) and its high potential to contribute to innovation (Ignatius, 2015). To carry out design effectively and efficiently, some support is necessary for designers (Gericke, Kramer, & Roschuni, 2016). However, at present, a company's uptake of design support developed by academia and meeting the abovementioned challenges is low in general (Tomiyama et al., 2009). Developing and providing industry with design support facilitating designers is urgently necessary to address the abovementioned challenges.

Therefore, this article aims to propose a method to support the design of a reliable system that will ensure circularity. To do so, the proposed method extends failure mode and effect analysis (FMEA) (Lange, Leggett, & Baker, 2001) to analyze the cause–effect relationships among failures, ultimately aiming to identify the root causes that hinder circularity. The extended FMEA is developed and applied to a real case in the industrial sector for validation.

The remainder of this article is organized as follows: Section 2 provides a literature review of related work. Section 3 introduces a research methodology employed in this study. Section 4 describes the extended FMEA in detail, while Section 5 applies this method to a real industrial case. Sections 6 and 7 discuss the research results and present our conclusions and future work, respectively.

## 2 | THEORETICAL BACKGROUND

### 2.1 | Challenges to a circular economy

For ensuring to close the loops of products, components, and materials, manufacturing companies are required to extend their responsibilities in the product lifecycle (Cavalieri & Pezzotta, 2012). Since it is highly challenging for single manufacturers to cover their extended responsibilities, they often need to collaborate with external actors within or beyond their current value chain, such as service providers, third-party suppliers, and customers (Antikainen & Valkokari, 2016; Parida, Burström, Visnjic, & Wincent, 2019; Stewart, Niero, Murdock, & Olsen, 2018). Therefore, manufacturers face the challenge of addressing interactions with multiple actors in order to ensure to close the loops while simultaneously remaining competitive on the markets. To this end, many studies have emphasized the critical need for a systems perspective in environmental analysis and decision-making (Allenby, 2006; Lifset & Graedel, 1997; NRC et al., 2014), enabling companies to identify opportunities for adding value to their offerings or reducing costs along their value chain both within their own production processes and beyond (Esty & Porter, 1998; Frosch, 1992). This means that, at the same time, manufacturers' scope of design has expanded to encompass larger systems involving various actors to provide products as well as services for ensuring to close the loops.

### 2.2 | System design methods for reducing environmental loads and enhancing system reliability

In the field of industrial symbiosis and industrial ecology, several tools have been developed for designing and optimizing a system that involves various actors, for which optimal matches among output and input streams can be derived (Yeo et al., 2019). For example, Cimren, Fiksel, Posner, and Sikdar (2011) developed a tool for designing an optimal network and material flows that utilized industrial by-products as feedstocks for other industrial processes, that is, by-product synergy. Leong, Lee, and Chew (2016) proposed a design methodology that enables individual plants to cooperate with each other so as to achieve greater water and energy recovery through interplant chilled/cooling water reuse/recycle. Recently, many researchers have been working on product-service systems (PSSs) as a means for realizing CE (Tukker, 2015). Kjaer, Pigosso, McAloone, and Birkved (2018) developed a guideline for evaluating the environmental performance of PSSs based on the life cycle assessment (LCA) methodology. They also proposed a framework for analyzing the potentials of PSSs with regard to CE (Kjaer, Pigosso, Niero, Bech, & McAloone, 2019).

Designing these systems requires not only reducing environmental loads but also enhancing the reliability of actors' processes for ensuring their commitments, such as a stable supply of products/materials. For this purpose, several methods have been developed for reducing environmental loads as well as for enhancing system reliability. For example, in the context of supply chains and logistics, Vahdani, Tavakkoli-Moghaddam, Modarres, and Baboli (2012) developed a model for designing a reliable network of facilities in closed-loop supply chains under uncertainty. Hatefi and Jolai (2014) proposed a robust and reliable model for an integrated forward–reverse logistics network design, one which simultaneously takes uncertain parameters and facility disruptions into account. Karimi and Niknamfar (2017) investigated a mathematical model for inventory strategies that considers system reliability in a green supply chain, including a single manufacturer and multiple retailers. In the field of industrial symbiosis and industrial ecology, Hsu and Rohmer (2010) proposed a probability-based method for assessing the reliability of synergistic systems and their ability to cope with the uncertainties associated with manufacturing and storage department activities. Wu, Guo, Li, and Qi (2017) proposed a framework for analyzing and quantifying the impact of redundancy on symbiotic system stability.

These methods focus on particular failures, such as those of resource shortage (Hsu & Rohmer, 2010; Wu et al., 2017), production capacity (Hsu & Rohmer, 2010; Karimi & Niknamfar, 2017; Wu et al., 2017), and logistics network facilities (Hatefi & Jolai, 2014; Vahdani et al., 2012). On the other hand, for enhancing system reliability, it is crucial to detect possible failures exhaustively and then to take adequate countermeasures against them, especially in early-stage design. To this end, FMEA is widely used in industries. FMEA, which was originally developed by the US military (MIL-STD-1629, 1980), is an engineering technique used to identify, prioritize, and eliminate potential failures from a system under design before a product in the system is released. Services related to a product were also incorporated into a unit of analysis and design by modifying FMEA (Kimita, Sakao, & Shimomura, 2018). Many researchers have extended FMEA to detect possible failures and analyze their environmental loads; this extension is called environment failure mode and effect analysis (EFMEA). These methods evaluate the environmental loads caused by product and/or process failures from the viewpoints of greenhouse gas emissions (Bayat, Farnood Ahmadi, & Ardeshir, 2018; Ćirović, 2018), waste (Bayat et al., 2018; Foroozesh, Tavakkoli-Moghaddam, & Meysam Mousavi, 2017; Kokangül, Polat, & Dağsuyu, 2018; Saadi, Djebabra, & Boulagouas, 2017; Salati & Jozi, 2012), pollution (Foroozesh et al., 2017; Jozi & Salati, 2012; Makajic-Nikolic, Petrovic, Cirovic, Vujosevic, & Presburger-Ulnikovic, 2016; Saadi et al., 2017; Salati & Jozi, 2012), energy consumption (Foroozesh et al., 2017), and recycling potential (Salati & Jozi, 2012). Lindahl and Tingström (2001) introduced other criteria, such as environmental policy or law, extent and time range of environmental effects, and improvement possibility. In EFMEA, these criteria are often estimated qualitatively based on expert judgement (Kania, Roszak, & Spilka, 2014; Lindahl & Tingström, 2001; Wan, Li, Ye, & Wang, 2019).

### 2.3 | Research challenge in failure analysis for enhancing circularity

As reviewed above, it is crucial to enhance system reliability for ensuring to close the loops of products, components, and materials. For this purpose, EFMEA could be effective in detecting possible failures from a system and then taking adequate countermeasures against them in early-stage design. However, existing methods, including EFMEA, fail to consider the cause–effect relationships among failures. Since these systems include interdependencies with the various actors involved, a failure by one actor could cause disruptions in the processes of the other actors involved (Hsu & Rohmer, 2010). For example, the processes of a company that builds on reusing, remanufacturing, and recycling products are largely influenced by those of other actors, such as maintenance providers and reverse logistics partners (Cao, Folan, Potter, & Browne, 2011; Guide Jr, 2000; Sakao & Sundin, 2019). The limited consideration of such cause–effect relationships will hinder manufacturers from identifying core problems that should be addressed to more efficiently ensure circularity.

## 3 | RESEARCH METHODOLOGY

This study builds upon the concept of FMEA to address the research challenge outlined above. Therefore, we extend the worksheet of FMEA and develop circularity failure mode and effect analysis (CFMEA). Here, *circularity* is defined for a system on question as the fraction of products derived from recycled or reused sources (Linder, Sarasini, & van Loon, 2017). Therefore, the method aims to detect possible failures that could decrease circularity. For enhancing circularity, therefore, the method focuses on failures related to the demand side of recycled or reused sources as well as the supply side. Furthermore, the cause–effect relationships among failures can be analyzed with CFMEA in order to develop effective countermeasures. FMEA is adopted due to two reasons. First, it is an established method for handling design failures in a systematic manner. Second, it is one of the most widely used methods for an early stage of design in the manufacturing industry (Booker, 2012) and is thus promising for higher uptake by industry.

To develop CFMEA, this study employed the hypothetical-deductive approach, which involves the development of a conceptual and theoretical structure, prior to empirical testing (Gill & Johnson, 2002). CFMEA was developed through three phases: (1) theoretical development, (2) empirical development, and (3) theory testing. In the theoretical development, a worksheet and its application procedure were developed based on the literature review introduced in Section 2.2. In the empirical development, the hypothetical CFMEA was improved through a workshop with a senior manager at the case company. Finally, in the theory testing phase, the effectiveness of the final version of CFMEA was tested through the second workshop.

## 4 | CIRCULARITY FAILURE MODE AND EFFECT ANALYSIS

### 4.1 | Approach of the proposed design support

Based on the worksheet of process FMEA, which is used to assess manufacturing process weaknesses and the potential effects of process failures on the product being manufactured (Chang, Chang, Wen, & Cheng, 2012), we propose a worksheet of CFMEA as shown in Table 1. Columns

**TABLE 1** A worksheet for circularity failure mode and effect analysis (CFMEA) with some example descriptions

| Items | | Characteristic of failures | | | Rating: Circularity | | | | | | Rating: *Cause–effect relationship* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Stakeholder*** | ***Required process elements for circulation*** | Failure mode | | Causes of failure | Probability | Current process and organization controls | Detection | ***Impacts on circularity*** | ***Severity*** | ***CRPN***[a] | ***Other failure modes affected*** | ***Net cause or effect*** | Countermeasures |
| Manufacturer | Procuring recycled materials | F1 | Shortage of recycled materials | Decrease in the amount of recycled materials in the market | 5 | Checked by an ad hoc process | 3 | Decrease in the amount of recycled materials | 1 | 15 | F8 | 2 | Increasing the collection rate of used products |
| | | F2 | Shortage of used products | Decrease in the number of collected products | 3 | Checked by an ad hoc process | 3 | Decrease in the number of reusable products | 1 | 9 | F8 | −1 | Building long-term relationship with product users |
| | | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| | Producing products | F5 | Inefficiency of the manufacturing process | Low quality of recycled materials | 3 | Checked by a formalized process | 1 | Increase in the amount of unrecoverable waste | 1 | 3 | F8 | 1 | Increasing the collection rate of used products |
| | | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| | Selling and delivering products | F8 | Decrease in the sales of recycled products | Decrease in the amount of recycled products for selling | 3 | Checked by an ad hoc process | 1 | Decrease in the amount of recycled products | 5 | 15 | F9 | −3 | None |
| | | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |

[a] CRPN, circularity risk priority number.

*Note.* Columns with bold and italicized text are points extended from the original process FMEA.

represented by bold and italic characters are the extension from the original process FMEA. In the same manner as Lange et al. (2001)) definition in the product field, this study defines a *failure* as the termination of the ability of an item to perform a required function. In CFMEA, the *item* corresponds to a process that influences circularity, which is the fraction of products derived from recycled or reused sources. Failures are detected from the entire system; then, they are evaluated from the viewpoint of the impacts they have on the ability of the entire system to ensure circularity. Furthermore, the cause–effect relationships among failures are analyzed, thereby revealing the root causes that decrease circularity in the entire system. Finally, countermeasures are developed based on a multi-criteria approach (Bovea & Pérez-Belis, 2012; Ramani et al., 2010) and on the basis of both circularity and the identified cause–effect relationships. In the following section, the details of the worksheet are introduced alongside the procedure.

## 4.2 | Procedure for circularity failure mode and effect analysis

### 4.2.1 | Step 1: Determination of items

In the same manner as the original FMEA (Lange et al., 2001; MIL-STD-1629, 1980), CFMEA considers an item as an elemental unit for analyzing failures. The process that influences circularity is described in the column of items. To clarify the boundary of the system and extract such processes exhaustively, the procedure begins with a description of the design object models that represent the entire system, including manufacturers as well as other stakeholders. First, a flow model (Sakao, Shimomura, Sundin, & Comstock, 2009) that represents the stakeholders involved in the system and their relationships is described. Based on the flow model, a function model is developed to represent the required functions for circularity. These functions are represented as the input/output relationships of "energy," "material," and "information" in the same manner as in Rodenacker (1970) and are subsequently decomposed into process elements. Finally, the processes are described in the item column as shown in Table 1, such as "procuring recycled materials." In this column, the stakeholders that assume these process elements are also described, such as "manufacturer."

### 4.2.2 | Step 2: Analysis of failure modes

In general, it is a challenge for designers to predict possible failures exhaustively in the early design stage, especially with a new product or service design. To help designers, FMEA analyzes a failure from the viewpoint of *failure mode*, which is defined as "the way in which a product or process could fail to perform its desired function" (Lange et al., 2001). In the same manner as the traditional FMEA, the method detects failure modes based on the described processes. Multiple failure modes can be detected for each process element. For each failure mode, causes of the failures are clarified. Furthermore, current organizations and processes that control the causes of failures are described. If there is no relevant organization and process, nothing is described in this column. For example, as shown in Table 1, "shortage of recycled materials (F1)" is extracted as a failure mode of "procuring recycled materials." A cause of this failure mode corresponds to a "decrease in the amount of recycled materials in the market." Furthermore, this cause of the failure mode is "checked by an ad hoc process" as described in the column of current process and organization controls.

### 4.2.3 | Step 3: Prioritization

The risk priority number (RPN) designates the priority levels of the failures that should be addressed in the design. CFMEA calculates the RPN from the viewpoint of circularity, that is, the circularity risk priority number (CRPN), via the multiplication of probability, detection, and severity. *Probability* represents the occurrence frequency of failure modes, which are evaluated on a five-point scale ranging from "1: rarely occurs" to "5: frequently occurs." For example, as shown in Table 1, the probability of "shortage of recycled materials (F1)" corresponds to 5, that is, it frequently occurs. *Detection* indicates the relative capacities of control processes and organizations to detect the occurrence of failures as well as their causes. With reference to "current process and organization controls," the likelihood of detecting a cause of a failure is evaluated on a five-point scale ranging from "1: almost certain" to "5: absolute uncertainty." For example, the detection of "shortage of recycled materials (F1)" corresponds to 3, that is, neutral likelihood. *Severity* represents the magnitude of the impact on circularity of the system on question. In the column named "circularity," the impacts on circularity are initially described. Then, their severity is evaluated with the following scale:

Large (5)—it will be difficult for the system to continue to function, resulting in the loss of the product derived from recycled or reused sources
Moderate (3)—the system will be degraded, but it can continue to function with decreased circularity
Small (1)—the system will be degraded, but it can be recovered by an alternate means without a decrease in circularity

Note that, for example, LCA, is not carried out due to a lack of the necessary quantitative and detailed information in the early stages of design. For example, as shown in the "circularity" column in Table 1, "decrease in the amount of recycled materials" is described as an impact on circularity that is caused by the failure mode, "shortage of recycled materials (F1)," and its severity is scored 1, that is, small. Finally, the CRPN is calculated by the multiplication of probability, detection, and severity. Failure modes with large CRPNs have the potential to significantly decrease circularity. For example, the CRPN of "shortage of recycled materials (F1)" is 15.

The cause–effect relationship for each failure mode refers to how many effects are given to or received from other failures. It is quantified as shown in the column "net cause or effect." To do so, first, other failure modes that are affected by each failure mode are extracted. Then, their cause–effect relationships are quantified using the Decision Making Trial and Evaluation Laboratory (DEMATEL) method, which is an effective technique for identifying the cause–effect chain components of a complex system (Malone, 1975), including green supply chains (Tirkolaee, Mardani, Dashtian, Soltani, & Weber, 2020) and industrial symbiosis (Bacudio et al., 2016). The procedure for calculating the system impact with the DEMATEL method is summarized as follows:

1. Generating the direct relation matrix. The direct influence between any two failure modes is evaluated by a score ranging from 0, 1, 2, and 5, representing "no influence," "low influence," "medium influence," and "high influence," respectively. An initial direct relation matrix $A = [a_{ij}]$ is a $n \times n$ matrix, where $a_{ij}$ is denoted as the degree to which failure mode $i$ affects failure mode $j$.
2. Normalizing the direct relation matrix. Based on the direct relation matrix $A$, the normalized direct relation matrix $X$ can be obtained through Equation (1):

$$X = k \times A \tag{1}$$

where

$$k = \min\left[\frac{1}{\left(\max 1 \leq i \leq n\sum_{j=1}^{n}|a_{ij}|\right)}, \frac{1}{\left(\max 1 \leq j \leq n\sum_{i=1}^{n}|a_{ij}|\right)}\right]$$

3. Calculating the total relation matrix. The total relation matrix $T$ is defined by Equation (2):

$$T = X(I - X)^{-1} \tag{2}$$

where $I$ is the identity matrix.

The sum of rows and the sum of columns are separately denoted as vectors $r_i$ and $c_j$ within the total relation matrix $T$; $r_i$ shows the sum of the direct and indirect effects of failure mode $i$ on the other failure modes. Similarly, $c_j$ shows the sum of the direct and indirect effects that failure mode $j$ has received from the other failure modes. When $j = i$, the difference $(r_i - c_j)$ depicts the net cause or effect that a failure mode $i$ contributes to the system. Specifically, if $(r_i - c_j)$ is positive, a failure mode $i$ is regarded as a cause factor, while a failure mode $i$ is regarded as an effect factor if $(r_i - c_j)$ is negative. The net cause or effect is normalized, with the maximum value corresponding to 5 or the minimum value corresponding to −5.

For example, as shown in the "cause–effect relationship" column in Table 1, "decrease in the sales of recycled products (F8)" is identified as a failure mode affected by the following failure mode: "shortage of recycled materials (F1)," the net cause of which corresponds to 2. In the same manner as existing EFMEA (Kania et al., 2014; Lindahl & Tingström, 2001; Wan et al., 2019) and DEMATEL methods (Bacudio et al., 2016; Tirkolaee et al., 2020), this process is performed qualitatively based on expert judgement. The design object models and the worksheet of CFMEA enable multiple experts to share their knowledge effectively in a complementary manner, thereby clarifying evidences of the judgement and enhancing its validation.

#### 4.2.4 | Step 4: Developing countermeasures

Finally, countermeasures against each failure mode are developed based on its CRPN and cause–effect relationship. With regard to failure modes with high CRPNs, if they are cause factors, that is, the score of the net cause or effect is positive, they should be prioritized by the focal company to develop countermeasures. This is because this type of failure mode could not only cause a large decrease in circularity but could also cause other failures. On the other hand, if they are effect factors, that is, the score of the net cause or effect is negative, then they can be considered as being caused by other failures. In this case, it is difficult to prevent this type of failure mode directly, and therefore countermeasures that address their root causes should be developed. Root causes can be identified with the result of the DEMAEL method. Furthermore, if root causes are failure modes of other actors, then countermeasures should be developed in collaboration with these actors. With regard to failure modes with low CRPNs, they

**FIGURE 1** Products in the case study—core plugs for the paper mill industry

should be prioritized to develop countermeasures only if they correspond to cause factors; they may cause other failure modes with large impacts on circularity even if their direct impacts on circularity are small.

Countermeasures can be developed through two types of design approaches: foolproof and fail-safe. Foolproof design aims to prevent failures, while fail-safe design aims to reduce the impact on circularity when failures occur. Furthermore, these designs can be performed at three levels: process, resource, and actor network levels (Kimita & Shimomura, 2014). Design at the process level is to add new or improve existing processes, while one at the resource level focuses on resource required to perform the processes, such as products and the organization. Design at the network level aims to change actors and/or their relationships in the system.

## 5 | APPLICATION OF CIRCULARITY FAILURE MODE AND EFFECT ANALYSIS

### 5.1 | Case description and methodology

PolyPlank AB uses recycled plastics and wood fibers (PolyPlank material) to manufacture a wide range of products in the construction and paper mill industries. Products used in the construction industry include the building of floors, fences, and balconies, among others. In the paper mill industry, PolyPlank AB produces core plugs, as shown in Figure 1. These core plugs are used in the paper mill industry to roll paper around them.

PolyPlank AB's business offering has been previously documented in the literature (Lindahl, Sundin, & Sakao, 2014). It consists of the recovery of used core plugs and their consequent cleaning or remanufacturing for further use through close collaboration with customers. The company is interested in securing its long-term profitability and environmental sustainability. As an early design stage aimed at improving the company's business, CFMEA was applied to detect and evaluate failures from the lifecycle perspective, from the initial acquisition of recycled plastics and wood fibers to their transportation, use, return, cleaning, and, when necessary, remanufacturing. To this end, workshops were carried out twice with a senior manager at PolyPlank's office in Malmö, Sweden. The first workshop was held on November 17, 2017, and lasted for 2.5 hrs. The first hour was dedicated to introducing the design support and to illustrating examples of its previous use in traditional FMEA. During the remainder of the workshop, the design object models of PolyPlank AB's current business were described, after which possible failure modes were extracted. Later, the requisite information was collected to evaluate the priorities of these failure modes. An evaluation of the failure modes was conducted after the workshop. The second workshop was held on March 7, 2018, and lasted for 2 hrs. The aim of this workshop was to present the results and to develop countermeasures. Furthermore, feedback and reflections on the implications of using this kind of tool were obtained.

Table 2 shows some of the results of applying CFMEA; the results are fully described in Supporting Information S1. In the following sections, these results are explained in more detail in accordance with the proposed procedure.

### 5.2 | Results of the application

#### 5.2.1 | Step 1: Determination of items

First, a flow model was described to define the target scope of the failure analysis. Figure 2a shows the description of the flow model, which consists of five stakeholders related to the circularity of core plugs. The material suppliers provide recycled plastic to the core plug manufacturer. The

**TABLE 2** Results of applying CFMEA to the case (excerpt from process elements related to the core plug manufacturer)

| Items | | Characteristic of failures | | | Rating | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Circularity | | | | | | Cause–effect relationship | | |
| Stakeholder | Required process elements for circulation | Failure mode | | Causes of failure | Probability | Current process and organization controls | Detection | Impacts on circularity | Severity | CRPN[b] | Other failure modes affected | Net cause or effect | Countermeasure[a] |
| Core plug manufac-turer | Procuring recycled plastic | F5 | Shortage of recycled plastic | Decrease in the amount of recycled plastic in the market | 3 | Checked by an ad hoc process | 3 | Decrease in the amount of recycled plastic | 1 | 9 | F12 (5) | 1 | Increasing the collection rate of used core plugs (Fs, P) |
| | | F6 | Shortage of used core plugs | Decrease in the number of collected used core plugs | 3 | Checked by an ad hoc process | 3 | Decrease in the number of reusable core plugs | 1 | 9 | F12 (5) | −1 | Building long-term relationship with the packaging company (Fp, N) |
| | | F7 | Low quality of recycled plastic | Inadequate production of recycled plastic | 3 | Checked by an ad hoc process | 3 | None | 0 | 0 | F11 (5) | 0 | Increasing the collection rate of used core plugs (Fs, P) |
| | | F8 | Low quality of used core plugs | Inadequate collection of used core plugs | 3 | Checked by an ad hoc process | 3 | None | 0 | 0 | F10 (5) | 0 | Making a direct contract with the packaging company (Fp, N) |
| | Manufacturing or reusing core plugs | F9 | Inadequate design of core plugs | Lack of knowledge on use of core plugs | 1 | Checked by a formalized process | 1 | None | 0 | 0 | F15 (5), F16 (5) | 2 | Putting serial numbers on core plugs (Fp, R) |
| | | F11 | Inefficiency of the man-ufacturing process | Low quality of recycled plastic | 2 | Checked by a formalized process | 1 | Increase in the amount of unrecover-able waste | 3 | 6 | F12 (2) | −1 | Increasing the collection rate of used core plugs (Fs, P) |

(Continues)

**TABLE 2** (Continued)

| Items | | Characteristic of failures | | | Rating | | | | | | | | Countermeasure[a] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Circularity | | | | | | Cause–effect relationship | | |
| Stakeholder | Required process elements for circulation | Failure mode | | Causes of failure | Probability | Current process and organization controls | Detection | Impacts on circularity | Severity | CRPN[b] | Other failure modes affected | Net cause or effect | |
| | Selling and delivering core plugs | F12 | Decrease in the sales of core plugs | Decrease in the number of core plugs for sale | 3 | Checked by an ad hoc process | 3 | Decrease in the number of core plugs | 3 | 27 | F13 (5) | −5 | Increasing the collection rate of used core plugs (Fp, P); Building long-term relationship with the packaging company (Fp, N) |
| Items | | Characteristic of failures | | | Rating | | | | | | | | Countermeasure[a] |
| | | | | | Circularity | | | | | | Cause–effect relationship | | |
| Stakeholder | Required process elements for circulation | Failure mode | | Causes of failure | Probability | Current process and organization controls | Detection | Impacts on circularity | Severity | CRPN | Other failure modes affected | Net cause or effect | |
| Paper mills | Procuring core plugs | F13 | Shortage of core plugs | Decrease in the number of core plugs in the market | 3 | None | 5 | Decrease in the number of core plugs | 3 | 45 | F17 (5), F14 (5) | 0 | None |
| | | F14 | Switch to substitutions made of virgin feedstock | Decrease in the number of core plugs in the market | 3 | None | 5 | Decrease in the number of core plugs. Increase in the number of substitutions made of virgin feedstock | 5 | 75 | F12 (5), F17 (5) | 1 | Building long-term relationship with the packaging company (Fp, N) |

(Continues)

**TABLE 2** (Continued)

| Items | | Characteristic of failures | | | Rating | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Circularity | | | | | | Cause–effect relationship | | |
| Stakeholder | Required process elements for circulation | Failure mode | | Causes of failure | Probability | Current process and organization controls | Detection | Impacts on circularity | Severity | CRPN[b] | Other failure modes affected | Net cause or effect | Countermeasure[a] |
| | Manufacturing paper | F15 | Cracking of a core plug | Degradation of core plugs | 3 | None | 5 | Increase in the number of non-reusable core plugs | 3 | 45 | F17 (2) | −1 | None |
| | Manufacturing package | F19 | Inadequate use of core plugs | Lack of knowledge on use of core plugs | 4 | None | 5 | None | 0 | 0 | F8 (5), F22 (1) | 1 | None |
| | | F20 | Inadequate disposal of core plugs | Lack of knowledge on disposal of core plugs | 4 | None | 5 | Increase in the number of non-reusable core plugs | 3 | 60 | F21 (5), F22 (1) | 2 | Making a direct contract with the packaging company (Fp, N) |
| Core plug collection company | Collecting used core plugs | F21 | Termination of collecting used core plugs | Decrease in the incentive to collect used core plugs | 3 | None | 5 | Decrease in the number of reusable core plugs | 3 | 45 | F6 (5) | −2 | Making a direct contract with the packaging company (Fp, N) |
| | Shipping used core plugs | F22 | Delay in shipping | Decrease in the number of core plugs for collecting | 3 | Checked by reactive processes | 4 | Decrease in the number of reusable core plugs | 3 | 36 | F6 (2) | −1 | None |

[a] Fp, foolproof; Fs, fail-safe; P, process level; R, resource level; N, network level.
[b] CRPN, circularity risk priority number.

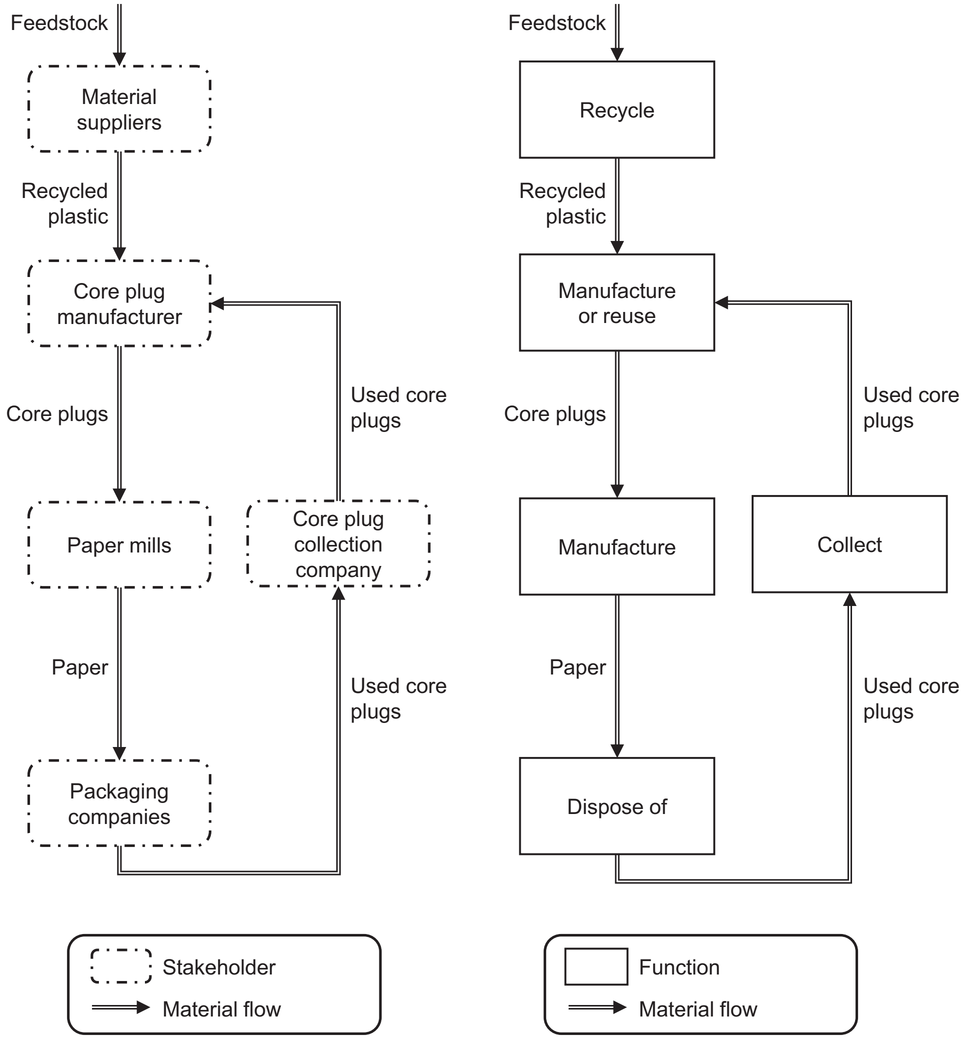


**FIGURE 2** A flow model and function model related to the circularity of core plugs

paper mills purchase core plugs and produce rolled papers fixed by the core plugs. Rolled papers are provided to packaging companies and used for packaged goods, such as milk cartons. Used core plugs are collected from packaging companies, then reused or recycled into new plugs by the core plug manufacturer. Based on the flow model, as shown in Figure 2b, a function model was developed to represent the required functions for ensuring the circularity of core plugs. Subsequently, these functions were decomposed into process elements. Figure 3 shows the sequence of the process elements and stakeholders who take responsibility for each process element. For example, the core plug manufacturer procures recycled plastic from the material suppliers, manufactures or reuses core plugs, and then sells and/or delivers them to the paper mills.

As shown in the left column of Table 2, the relevant process elements were described. For example, manufacturing or reusing core plugs and selling and delivering core plugs were described as process elements that were assumed by the core plug manufacturer.

### 5.2.2 | Step 2: Analysis of failure modes

Next, failure modes were detected based on the process elements. The center column in Table 2 shows an example of the detected failure modes. For example, "shortage of recycled plastic (F5)," "shortage of used core plugs (F6)," and "low quality of recycled plastic (F7)" were detected as failure modes of the process element, "procuring recycled plastic." For each failure mode, the causes of failure were subsequently clarified. For example, "decrease in the amount of recycled plastic in the market" was identified as a cause of the failure mode, "shortage of recycled plastic (F5)"; whereas "decrease in the number of collected used core plugs" was identified as a cause of "shortage of used core plugs (F6)" and "inadequate production of recycled plastic" was identified as a cause of "low quality of recycled plastic (F7)." Furthermore, the current process and organization that controls the cause of each failure were described. In this application, this column was filled out from the viewpoint of the core plug manufacturer so that it

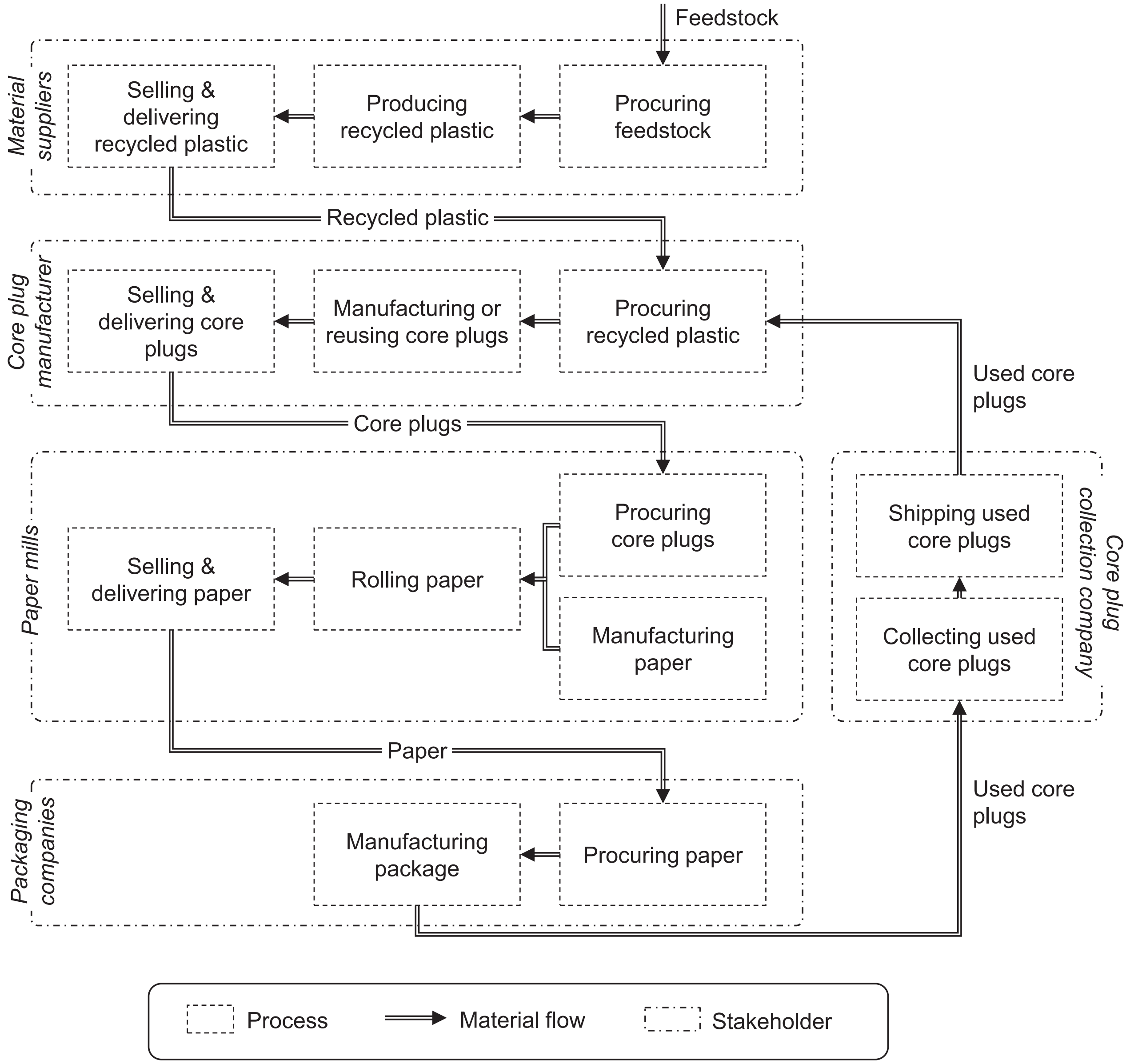


**FIGURE 3** Process elements and stakeholders related to the circularity of core plugs

could develop effective countermeasures against failures. For example, “shortage of recycled plastic (F5)” was “checked by an ad hoc process” by the core plug manufacturer.

### 5.2.3 | Step 3: Prioritization

Subsequently, the CRPN was determined to indicate the priority of each failure mode to be addressed. Based on an interview with the core plug manufacturer, probability was first evaluated using a five-point scale ranging from “1: rarely occurs” to “5: frequently occurs.” With reference to “current process and organization controls,” detection was also evaluated using a five-point scale ranging from “1: almost certain” to “5: absolute uncertainty.” For example, the probability and detection of “shortage of recycled plastic (F5)” was 3 (neutral). Severity was evaluated from the viewpoint of impacts on the circularity of the entire system. In the “circularity” column, first, impacts on circularity were described; second, their severity was evaluated. In this application, the severity of impacts on circularity was evaluated based on an interview with the manager of the core plug manufacturer. For example, with regard to “shortage of recycled plastic (F5),” “decrease in the amount of recycled plastic” was described as an impact on circularity, thereby its severity was evaluated as 1, that is, low, since it could be compensated for by the collection of used core plugs. The severity of “iffigurenefficiency of the manufacturing process (F11)” was evaluated as 3, since it causes the increase in the amount of

**TABLE 3** Result of circularity risk priority number (CRPN) and net cause or effect

| Stakeholders | | Failure modes | CRPN[a] | Net cause or effect |
|---|---|---|---|---|
| Material suppliers | F1 | Shortage of feedstock | 15 | 2 |
| | F2 | Low quality of feedstock | 0 | 1 |
| | F3 | Inefficiency of the recycling process | 30 | 0 |
| | F4 | Decrease in the sales of recycled plastic | 5 | 0 |
| Core plug manufacturer | F5 | Shortage of recycled plastic | 9 | 1 |
| | F6 | Shortage of used core plugs | 9 | −1 |
| | F7 | Low quality of recycled plastic | 0 | 0 |
| | F8 | Low quality of used core plugs | 0 | 0 |
| | F9 | Inadequate design of core plugs | 0 | 2 |
| | F10 | Inefficiency of cleaning or remanufacturing | 6 | −1 |
| | F11 | Inefficiency of the manufacturing process | 6 | −1 |
| | F12 | Decrease in the sales of core plugs | 27 | −5 |
| Paper mills | F13 | Shortage of core plugs | 45 | 0 |
| | F14 | Switch to substitutions made of virgin feedstock | 75 | 1 |
| | F15 | Cracking of a core plug | 45 | −1 |
| | F16 | Cracking of a core plug | 45 | −1 |
| | F17 | Decrease in the sales of paper mills with core plugs | 45 | −5 |
| Packaging company | F18 | Shortage of paper mills with core plugs | 45 | −2 |
| | F19 | Inadequate use of core plugs | 0 | 1 |
| | F20 | Inadequate disposal of core plugs | 60 | 2 |
| Core plug collection company | F21 | Termination of collecting used core plugs | 45 | −2 |
| | F22 | Delay in shipping | 36 | −1 |

[a] CRPN, circularity risk priority number.

unrecoverable waste during the manufacturing processes. The severity of “switch to substitutions made of virgin feedstock (F14)” was evaluated as 5, since disruptions here could adversely impact the entire system, resulting in the loss of the products derived from recycled or reused sources, that is, core plugs. Finally, the CRPN was calculated via the multiplication of probability, detection, and severity as shown in Table 3. Failure modes with high CRPNs include “switch to substitutions made of virgin feedstock (F14),” “inadequate disposal of core plugs (F20),” and “termination of collecting used core plugs (F21).”

The cause–effect relationships among these failure modes were analyzed using the DEMATEL method. First, we identified failure modes that were affected by other failure modes, as shown in the column “other failure modes affected” in Table 2. For example, “shortage of recycled plastic (F5)” affects “decrease in the sales of core plugs (F12),” since F5 decreases the number of core plugs available for selling. Based on this information, we developed a direct relation matrix, in which the direct influence between any two failure modes was evaluated by a score ranging from “0: no influence” to “5: high influence.” Numbers in parentheses in the column “other failure modes affected” show the direct influence. The results are fully described in Supporting Information S2. Normalizing the direct relation matrix, the total relation matrix was calculated by Equation (2). The total relation matrix is shown in Figure 4. Each number in the table, which was calculated by Equations (1) and (2), shows direct and indirect influences that the failure mode in the row has on the failure mode in the column. For example, “shortage of recycled plastic (F5)” and “shortage of used core plugs (F6)” have a large influence on “decrease in the sales of core plugs (F12),” that is, 0.6. Furthermore, $r$ shows the sum of the direct and indirect effects of a failure mode in the row on the other failure modes in the columns, while $c$ shows the sum of the direct and indirect effects that a failure mode in the column has received from the other failure modes in the rows. For example, “decrease in the sales of core plugs (F12)” not only provides large effects on the other failure modes ($r = 1.9$) but also receives large effects from the other failure modes ($c = 4.6$). Finally, the score of net cause or effect was calculated based on the normalized values of ($r_i - c_j$), where the minimum value corresponded to −5. As shown in Table 3, failure modes that have large effects on other failures include “shortage of feedstock (F1),” “inadequate design of core plugs (F9),” and “inadequate disposal of core plugs (F20).” On the other hand, failure modes that are greatly affected by other failures include “decrease in the sales of core plugs (F12)” and “decrease in the sales of paper mills with core plugs (F17).”

| Stakeholders | Failure modes | | F1 | F2 | F3 | F4 | F5 | F6 | F7 | F8 | F9 | F10 | F11 | F12 | F13 | F14 | F15 | F16 | F17 | F18 | F19 | F20 | F21 | F22 | ***r**** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Material suppliers | F1 | Shortage of feedstock | 0 | 0 | 0 | 0.5 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.1 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | **1.1** |
| | F2 | Low quality of feedstock | 0 | 0 | 0.5 | 0.1 | 0.1 | 0 | 0.1 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0.9** |
| | F3 | Inefficiency of the recycling process | 0 | 0 | 0 | 0.2 | 0.1 | 0 | 0.2 | 0 | 0 | 0 | 0.1 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0.8** |
| | F4 | Decrease in the sales of recycled plastic | 0 | 0 | 0 | 0 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.1 | 0.1 | 0 | 0 | 0.1 | 0.1 | 0 | 0 | 0 | 0 | **1.2** |
| Core plug manufacturer | F5 | Shortage of recycled plastic | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0.3 | 0.1 | 0 | 0 | 0.2 | 0.1 | 0 | 0 | 0.1 | 0 | **1.5** |
| | F6 | Shortage of used core plugs | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0.3 | 0.1 | 0 | 0 | 0.2 | 0.1 | 0 | 0 | 0.1 | 0 | **1.5** |
| | F7 | Low quality of recycled plastic | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.1 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0.8** |
| | F8 | Low quality of used core plugs | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0 | 0.1 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0.8** |
| | F9 | Inadequate design of core plugs | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0.2 | 0.1 | 0 | 0 | 0.1 | 0 | **1.4** |
| | F10 | Inefficiency of cleaning or remanufacturing | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.1 | 0.1 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | **0.6** |
| | F11 | Inefficiency of the manufacturing process | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.1 | 0.1 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | **0.6** |
| | F12 | Decrease in the sales of core plugs | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.6 | 0.3 | 0 | 0 | 0.4 | 0.2 | 0 | 0 | 0.1 | 0 | **1.9** |
| Paper mills | F13 | Shortage of core plugs | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.4 | 0.2 | 0.6 | 0 | 0 | 0.9 | 0.4 | 0 | 0 | 0.2 | 0.1 | **2.9** |
| | F14 | Switch to substitutions made of virgin feedstock | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0.3 | 0.2 | 0 | 0 | 0.7 | 0.4 | 0 | 0 | 0.2 | 0.1 | **2.6** |
| | F15 | Cracking of a core plug | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.1 | 0 | 0 | 0.1 | 0 | **0.4** |
| | F16 | Cracking of a core plug | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.1 | 0 | 0 | 0.1 | 0 | **0.4** |
| | F17 | Decrease in the sales of paper mills with core plugs | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0 | 0 | 0.3 | 0.1 | **1.2** |
| Packaging company | F18 | Shortage of paper mills with core plugs | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.1 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0.5 | 0.2 | **1.4** |
| | F19 | Inadequate use of core plugs | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0 | 0.3 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | **1.0** |
| | F20 | Inadequate disposal of core plugs | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.1 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0.5 | 0.1 | **1.3** |
| Core plug collection company | F21 | Termination of collecting used core plugs | 0 | 0 | 0 | 0 | 0 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.1 | 0.1 | 0 | 0 | 0.1 | 0.1 | 0 | 0 | 0 | 0 | **1.2** |
| | F22 | Delay in shipping | 0 | 0 | 0 | 0 | 0 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0.5** |
| | | ***c**** | **0.0** | **0.0** | **0.5** | **0.8** | **0.9** | **2.0** | **0.3** | **0.5** | **0.0** | **0.8** | **0.7** | **4.6** | **2.8** | **1.9** | **0.5** | **0.5** | **3.9** | **2.5** | **0.0** | **0.0** | **2.2** | **0.9** | |

*Note.* Each number shows direct and indirect influences that the failure mode in the row has on the failure mode in the column.

*__r__ shows the sum of the direct and indirect effects of a failure mode in the row on the other failure modes in the column
***c*** shows the sum of the direct and indirect effects that a failure mode in the column has received from the other failure modes in the row

**FIGURE 4** Results of the DEMATEL method: the total relation matrix

### 5.2.4 | Step 4: Developing countermeasures

Finally, countermeasures against the failure modes were developed. In this application, we focused on the countermeasures that the core plug manufacturer could implement. With regard to failure modes, those with high CRPNs included "shortage of recycled plastic (F5)," "shortage of used core plugs (F6)," and "decrease in the sales of core plugs (F12)." F5 was prioritized to develop countermeasures by the company, that is, the core plug manufacturer, since it was a cause factor. As a result, "increasing the collection rate of used core plugs" was developed as a countermeasure at the process level, so that the company could compensate for the shortage of recycled plastic with used core plugs, that is, fail-safe for reducing the impact on circularity. On the other hand, since F6 and F12 are effect factors, countermeasures were developed in order to address their root causes. As shown in Figure 4, root causes of F12 included "shortage of recycled plastic (F5)," "shortage of used core plugs (F6)," and "switch to substitutions made of virgin feedstock (F14)." Since F14 belongs to the paper mills, the countermeasure at the actor network level was developed in collaboration with them. For preventing the failure mode, that is, foolproof, "building long-term relationship with the packaging company" was developed, encouraging the packaging company to purchase rolled papers with core plugs from the paper mills. With regard to F6, "termination of collecting used core plugs (F21)" was identified as a root cause. However, since F21 was also an effect factor, further investigation was conducted to identify its root causes. Finally, "inadequate disposal of core plugs (F20)" was identified as a root cause, thereby "making a direct contract with the packaging company" was developed to ensure its commitment to the collection of core plugs.

On the other hand, with regard to failure modes with low CRPNs, "inadequate design of core plugs causes (F9)" was identified as a cause factor. Although the decrease in circularity directly caused by this failure mode was small, it could cause *other* failures to occur with high CRPNs, such as "cracking of a core plug (F15 and F16)." Therefore, it was prioritized to develop countermeasures. "Putting serial numbers on core plugs" was developed as a countermeasure at the resource level, enabling the collection and analysis of data on product condition and use for improving the design of core plugs.

## 6 | DISCUSSION

### 6.1 | Effectiveness of the design support

The major theoretical contribution of CFMEA lies in its capability to detect failures from the entire system and to then evaluate them in terms of circularity. Also, the cause–effect relationships among failures can be analyzed with CFMEA to develop countermeasures that can more effectively solve failure-related problems. By applying CFMEA to an industrial system on the market, we have shown its effectiveness in the following ways. First, CFMEA enables the identification of failure modes that receive large influences from other failures and then develops effective countermeasures by addressing their root causes. For example, "decrease in the sales of core plugs (F12)" was found to be a failure mode that received large influences from other failure modes; accordingly, a countermeasure was developed to address its root cause: "switch to substitutions made of virgin feedstock (F14)." Since existing EFMEA fails to uncover the cause–effect relationships among failures, it has difficulty identifying their root causes. Second, CFMEA is also capable of identifying failure modes that have large effects on other failures. These failure modes might in turn cause other failures that have large impacts on circularity. Therefore, they should be prioritized to develop countermeasures, even if their direct impacts on circularity are small. In the application, "inadequate design of core plugs causes (F9)" was identified as a failure mode that had the potential to cause other failure modes with large impacts on circularity, such as "cracking of a core plug (F15 and F16)." Since F9 itself had a small impact on circularity, existing EFMEA would not depict its risk in this way. Third, CFMEA can identify failures of external actors that have large influences on the focal company. This enables to find an opportunity to collaborate with these actors to ensure circularity. In the application, "switch to substitutions made of virgin feedstock (F14)" was identified as a failure mode that had a large influence on the failure mode of the core plug manufacturer, that is, "decrease in the sales of core plugs (F12)." Since F14 belongs to the paper mills, the countermeasure was developed in collaboration with them. Finally, compared with methods that require sufficient quantitative data, such as that by Karimi and Niknamfar (2017), CFMEA is useful even in the early stages of design. The application's approach has been validated to extract and address failures based on the design object models. The flow model helped to determine the specific system boundaries for analyzing failures and assessing their impacts on circularity; meanwhile, the process model was effective for extracting failure modes. Importantly, the information required to describe the models is available in the conceptual design stage.

### 6.2 | Practical implications

According to feedback and reflections from the company, CFMEA was found to be effective in practical situations. In the application, "making a direct contract with the packaging company" was developed to ensure commitment to the collection of core plugs. Before the method's application, the core plug manufacturer had limited responsibility for the collection of core plugs and limited contacts with the packaging company and the core plug collection company. However, as a result of the analysis, it was revealed that failures on the part of these stakeholders are central to those of the core plug manufacturer, such as "shortage of used core plugs (F6)." Therefore, collaboration with the packaging company was considered for developing the countermeasure. Such collaborative processes among different stakeholders are crucial for sustainable system design (NRC et al. 2014; Ramani et al., 2010).

When using CFMEA in practice, failure modes are specified and evaluated and then countermeasures are developed based on users' domain knowledge and methodical expertise, such as how to assign scores. This expertise can be obtained from that for FMEA (Lange et al., 2001). Since FMEA is used extensively in the industry (Booker, 2012), obtaining this expertise is not considered as a challenge. If the focal company does not cover the complete domain knowledge, it is necessary to get information or knowledge from other actors in the system. As demonstrated in the application, the specification and evaluation require knowledge of the entire system, such as the product lifecycle and supply chain. Since the company was not aware of the entire process of collecting used core plugs, they sought information from other actors. Furthermore, the company had enough knowledge of failures related to the demand side for recycle and reuse of products and materials, but needed additional information to analyze those related to the supply side more effectively. However, once the CFMEA has been performed, the information and knowledge gathered from this exercise can be used in another CFMEA, where potential failures will be detected and addressed more efficiently. The discussion of this paragraph coincides with the positive effects that occur from collaborating with other actors in the concerned system for environmental performance (Chen, Wu, & Wu, 2015) and also for a circular economy (Leising, Quist, & Bocken, 2018).

### 6.3 | Limitations of the proposed design support

In the application, limitations on the effectiveness and efficiency of using CFMEA were noted in terms of company size and product type. Concerning company size, the manufacturer in the case study is a small- and medium-sized enterprise (SME), and therefore most of its information and risk judgments can be handled by one or a few employees. However, for large companies, this could present a challenge, since a big picture of the system could be lacking due to most employees being dedicated to specific areas. This makes it difficult to collect accurate and reliable data spreads within these companies. Therefore, additional supports, such as a guideline for collecting the requisite information, are required for using CFMEA effectively and efficiently.

Regarding product type, the manufacturer also produces planks for construction purposes. In discussing the possibilities of applying CFMEA to the product, CFMEA was deemed to be potentially unsuitable, since the lifetime of the product is approximately 50 years, leading to a long period of circulation. Analyzing the failures of products with long lifetimes requires considering changes in business environments for identifying and addressing potential failures. However, CFMEA could be applicable at the component level, since some components need to be replaced in a shorter term.

This article used the definition of circularity (Linder et al., 2017) for specificity, focusing on reuse and recycle. As clarified by Linder et al. (2017), this definition has a narrow focus implying both strength and weakness. With reference to the strength, CFMEA was found specifically useful for addressing failures related to reuse and recycle. One weakness is the risk of overlooking the opportunity to prolong the lifetime of products; however, this opportunity is likely to be taken by the feature of the traditional FMEA, which is inherently included in CFMEA.

## 7 | CONCLUSION

This paper proposed CFMEA from the perspectives of circularity and system reliability. Based on the results of the industrial application, CFMEA was found to be effective for identifying failure modes where effects are largely given to or received from other failures and then developing effective countermeasures by addressing their root causes. This also enables the identification of failures of external actors that have a large influence on the failures of the focal company, thereby revealing opportunities to collaborate with these actors to ensure circularity. Furthermore, CFMEA is useful even in the early stages of design. Future research will include developing additional supports for CFMEA so that the method can be more useful for large companies and quantitatively evaluating the eventual solutions of a detailed design based on the results of the case study.

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#### CONFLICT OF INTEREST

The authors declare no conflict of interest.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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